CHARNOCK INITIAL
REGIONAL RESPONSE ACTIVITIES (CIRRA)

Task 9
Conceptual Flow and Transport Model Report
Charnock Sub-Basin
Santa Monica, California

Submitted to:

California Regional Water Quality Control Board,
Los Angeles Region

U.S. Environmental Protection Agency,
Region IX

On behalf of:

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Shell Oil Products Company
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A C R O N Y M S AND A B B R E V I A T I O N S

ac-ft/ac	acre-feet per acre
ac-ft/yr	acre-feet per year
Agencies	California Regional Water Quality Control Board, Los Angeles Region and United States Environmental Protection Agency
AOC	Administrative Order on Consent (with USEPA)
Aquifer Report	Aquifer Characterization Report, July 1999, by Geomatrix
BEI	Bechtel Environmental, Inc.
bgs	below ground surface
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CDHS	California Department of Health Services
CDMG	Californian Division of Mines and Geology
CDOG	California Department of Oil and Gas
CDWR	California Department of Water Resources
Chevron	Chevron Products Company
COSM	City of Santa Monica
CWRA	Charnock Well Field Regional Assessment
DIPE	diisopropyl ether
EtOH	Ethanol
ETBE	Ethyl tert-butyl alcohol
Exxon	Exxon Company, USA
ft/day	feet per day (unit of measure of hydraulic conductivity)
Geomatrix	Geomatrix Consultants, Inc.
Geomatrix Report	Conceptual Hydrogeologic Model, December 18, 1997, Report by Geomatrix
gpd/ft	gallons per day per foot (unit of measure of transmissivity)
gpm	gallons per minute
gpm/ft	gallons per minute per foot of drawdown (unit of measure of specific capacity)
in/yr	inches per year (unit of measure for areal recharge)
Komex	Komex • H2O Science
LACDPW	Los Angeles County Department of Public Works
LADWP	Los Angeles Department of Water and Power
LAMWD	Los Angeles Metropolitan Water District
LNAPL	Light NAPL
msl	mean sea level
MeOH	Methanol
MTBE	methyl tertiary-butyl ether
NAPL	Non-Aqueous Phase Liquid
NCDC	National Climate Data Center
PAH	Polyaromatic Hydrocarbon

ACRONYMS AND ABBREVIATIONS (continued)

Report	ENVIRON's Conceptual Flow and Transport Model Report, Aug. 2000 (i.e., the current document)
RESNA	RESNA Industries, Inc.
Respondents	Shell Oil Company, Shell Oil Products Company and Equilon Enterprises LLC
RWQCB	California Regional Water Quality Control Board, Los Angeles Region
SA	Stipulated Agreement (of RWQCB)
SCWC	Southern California Water Company
TAME	tert-amyl methyl ether
TBA	tert-butyl alcohol
TBF	tert-butyl formate
TPHCWG	Total Petroleum Hydrocarbon Working Group (Gustafson et al., 1998)
USACE	United States Army Corps of Engineers
USCS	Unified Soil Classification System
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WY	water year (1 October to 30 September)

EXECUTIVE SUMMARY

Pursuant to the Scope of Work (SOW) of the California Regional Water Quality Control Board, Los Angeles Region (RWQCB) Stipulated Agreement (SA) No. 00-064 and the United States Environment Protection Agency, Region 9 (USEPA) Administrative Order on Consent (AOC) USEPA Docket No. RCRA 7003-09-2000-0003 (collectively the SA/AOC), this "Conceptual Flow and Transport Model Report for the Charnock Sub-Basin, Los Angeles, California" (the "Report") is submitted to the RWQCB and USEPA (the Agencies) by Shell Oil Company, Shell Oil Products Company and Equilon Enterprises LLC (the Respondents) in fulfillment of Task 9.

One of the more significant objectives of the SA/AOC is to evaluate groundwater flow and the movement of gasoline-related constituents, including methyl tertiary-butyl ether (MTBE), within the Charnock Sub-Basin[1] under current conditions and a variety of remedial action scenarios. Specific objectives of the SA/AOC include (SOW Task 10.1):

- evaluating measures needed to control the movement of groundwater affected by MTBE and protect areas of unaffected groundwater;
- evaluating potential measures to capture and remove MTBE-affected groundwater;
- providing a tool to manage the concurrent production and remediation of groundwater; and
- evaluating potential groundwater flow pathways from potential MTBE source areas.

These objectives will be addressed through development and application of a numerical model of groundwater flow and contaminant transport. The conceptual description of the hydrogeology of the Charnock Sub-Basin presented in this Report provides a technical basis for the construction and calibration of a numerical groundwater flow model. This Report presents compiled and interpreted data, provides analysis and assumptions comprising the conceptual hydrogeologic model, and lays the foundation for developing a detailed numerical model of groundwater flow.

[1] The SOW defines the Charnock Sub-Basin ("the Sub-Basin") as the area of Los Angeles and Culver City bounded by the Overland Fault to the east, the Ballona escarpment to the south, the Charnock Fault to the west, and the base of the Santa Monica Mountains to the north.

As stipulated in the SOW, this Report has been developed by revising and updating an earlier conceptual hydrogeologic model as described by Geomatrix Consultants (1997g), hereinafter referred to as the "Geomatrix Report." Aquifer properties were subsequently refined by aquifer tests and analyses and an electromagnetic borehole flowmeter (EBF) test by Geomatrix. These refinements were reported to the Agencies in the "Aquifer Characterization Report, Charnock Well Field Regional Assessment" (Geomatrix, 1999) (the "Aquifer Report"). In addition, aquifer properties have been developed and refined in numerical modeling tasks undertaken by Geomatrix, Respondents, Chevron Products Company ("Chevron"), and Exxon Company, USA ("Exxon"). These activities include model calibration and model parameter sensitivity analyses. In this Report, ENVIRON International Corporation ("ENVIRON"), has refined and updated the Geomatrix Report with data/information from the Aquifer Report. Both the Geomatrix Report and the Aquifer Report were produced as a part of the prior Charnock Well Field Regional Assessment (CWRA).

Approach

The elements of the conceptual flow and transport model needed to construct a numerical model of groundwater flow in the Charnock Sub-Basin include:

- a review of related previous work and available data (*Section 1, Introduction*);
- definition of the Charnock Sub-Basin and its boundaries in the context of the encompassing Santa Monica groundwater basin, the Charnock Sub-Basin's hydrostratigraphic units and structure, zones of groundwater saturation and patterns of groundwater fluctuation and movement (*Section 2, Hydrogeologic Setting*);
- definition of the hydraulic properties of the hydrostratigraphic units (*Section 3, Aquifer Properties*);
- definition of groundwater inflow, outflow, and change in storage (*Section 4, Sub-Basin Water Balance*);
- development of the approach for constructing, calibrating, and applying the numerical model of groundwater flow (*Section 5, Numerical Approach to Modeling*); and
- development of conceptual information regarding MTBE and other gasoline constituents' fate and transport (Section 6, *Chemical Fate and Transport).*

Previous Work and Available Data

The hydrogeology of the Los Angeles basin[2] has been studied since the early 1900s. Comprehensive investigations were conducted in the 1950s and early 1960s in response to concerns over potential overdraft and seawater intrusion. These previous reports provide an extensive source of information and hydrogeologic interpretation. Other available data include:

- lithologic logs from more than 400 borings and 18 geophysical logs
- well construction data from more than 300 water production wells and 500 vadose zone or groundwater monitoring wells
- groundwater levels from almost 300 wells
- groundwater chemistry from more than 100 wells
- groundwater extraction and injection records since 1931
- aquifer properties reported, measured, and estimated
- precipitation and climatic data
- rates of delivered municipal water.

The information in these historical records provides an important basis for the development of a conceptual hydrogeologic model of the Charnock Sub-Basin.

Hydrogeologic Setting

The Santa Monica Basin is bounded by the Inglewood Fault to the northeast, the Santa Monica Mountains to the northwest, the Pacific Ocean to the west and southwest, and the Ballona escarpment and Baldwin Hills to the south and southeast. It contains more than 5000 feet of Tertiary and Quaternary marine and continental sediments overlying a basement complex of pre-Tertiary metamorphic and igneous rocks. The Charnock and Overland Avenue Faults subdivide the Santa Monica Basin into the Coastal, Charnock, and Crestal Sub-Basins (see Figure 2-5). The West Coast groundwater basin lies south of the Ballona escarpment and Baldwin Hills.

The 3550-acre Charnock Sub-Basin lies between the Charnock and Overland Avenue Faults. Vertical displacements range up to 140 feet across the Charnock Fault and 30 feet across the Overland Avenue Fault. The Charnock Sub-Basin is down-dropped relative to the adjacent Coastal and Crestal Sub-Basins. Because vertical displacement has been greater on the Charnock Fault than on the Overland Avenue Fault, the geologic block that comprises the Charnock Sub-Basin has been tilted toward the southwest. Sediments of Recent geologic age are not appreciably offset by these faults.

The Santa Monica groundwater basin has served as a groundwater resource since the late 1800s. Relatively coarse-grained sediments of the San Pedro Formation, Lakewood Formation, and Recent alluvium comprise the primary water-producing units within the Sub-Basin. Of these, the Silverado aquifer of the lower Pleistocene San Pedro Formation has the greatest lateral extent and saturated thickness, and historically has been the source of much of the groundwater produced from the Sub-Basin. Beneath the Silverado aquifer are relatively low-permeability sediments of the lower San Pedro and upper Pico formations.

Groundwater recharge to the Santa Monica groundwater basin occurs through subsurface flow from the adjacent watersheds of the Santa Monica Mountains, deep percolation of precipitation and delivered water, and subsurface inflow across the basin's boundaries. Since the early 1900s, groundwater discharge has occurred primarily through groundwater extraction for agricultural and/or municipal uses. The Charnock Sub-Basin currently has two operable well fields in relative close proximity near the center of the Sub-Basin, one operated by the City of Santa Monica (COSM), and the other by the Southern California Water Company (SCWC)[3].

The hydrogeologic boundaries of the Charnock Sub-Basin and adjacent groundwater sub-basins are defined by the following:

- Northwest: Permeable sediments pinch out against the Santa Monica Mountains. Significant groundwater recharge occurs from the adjacent mountain watersheds to the north.
- Southeast: The Ballona escarpment and the Baldwin Hills, which form the southeast hydrogeologic boundary, contain three segments:

    - South-Southeast: Younger sediments of the Coastal and Charnock Sub-Basins abut the Ballona escarpment, an erosional feature southwest of the Baldwin Hills. The Silverado aquifer appears to extend beneath the escarpment into the West Coast basin. Groundwater flows between the Charnock Sub-Basin and the West Coast basin under the influence of hydraulic gradients controlled by groundwater pumping.
    - Mid-Southeast: The Silverado aquifer remains saturated beneath the southern part of the Baldwin Hills boundary, allowing groundwater to flow between the West Coast basin and the Charnock and Crestal Sub-Basins.
    - East-Southeast: Low-permeability strata form an effective barrier to groundwater flow in this area of the Baldwin Hills boundary of the Crestal Sub-Basin.

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[2] The Charnock Sub-Basin is a subarea of the larger Los Angeles basin as illustrated on Figure 1-1.

[3] The SCWC historically operated a second well field in the Sub-Basin (the SCWC Sepulveda well field) which ceased operation in 1960.

- Southwest: The northwest-trending Charnock Fault defines the southwestern boundary of the Charnock Sub-Basin. Groundwater level discontinuities across the fault indicate that it is a partial barrier to groundwater flow. However, shallow, saturated zones may be relatively continuous across the fault.
- Northeast: The northwest-trending Overland Avenue Fault defines the northeastern limit of the Charnock Sub-Basin. As with the Charnock Fault, groundwater level discontinuities indicate that it is a partial barrier to groundwater flow except in the shallowest zones.
- Basal: Relatively low-permeability sediments underlie the Silverado aquifer and define the effective lower boundary of the Sub-Basin.
- Upper: The regional water table is recharged by percolation of rainfall, runoff, introduced water, and perched groundwater.

Hydrostratigraphy

The hydrostratigraphy of the Charnock Sub-Basin was interpreted based on literature, geologic cross sections, a review of the nature and quality of the data, and vertical profiles of the incidence of well perforations and average lithologic texture. A review of the nature and quality of the data from these sources indicates general internal consistency. Consequently ENVIRON used this information to construct a three-dimensional model of the hydrostratigraphy.

The sedimentary deposits of the Charnock Sub-Basin comprise a heterogeneous section of sand, gravel, silt, and clay. The “50-Foot Gravel” or “Ballona aquifer” is the shallowest coarse-grained unit recognized in previous studies. Below this and above the Silverado aquifer are other recognized but unnamed aquifer zones of varying lithology. The Silverado aquifer is a 70- to 270-foot-thick interval of predominantly coarse-grained sediments that serves as the principal source of groundwater to pumping wells. Heterogeneous and locally discontinuous aquitard zones separate the various aquifer units.

The Geomatrix Report (1997g) presented a seven-hydrostratiographic-zone geologic structure of the Charnock Sub-Basin based on a detailed interpretation of more than 400 logs discretized into more than 100,000 one-half-foot (0.5 ft) intervals. The seven hydrostratigraphic zones in the Charnock Sub-Basin and adjacent areas of the Coastal and Crestal Sub-Basins, numbered from top (I) to bottom (VII), are described below:

- Zone I comprises predominantly fine-grained surficial sediments.
- Zone II corresponds to the Ballona aquifer and equivalent hydrostratigraphic units.
- Zones III and V are heterogeneous and locally discontinuous potential aquitards.

- Zone IV corresponds to heterogeneous but predominantly coarse-grained sediments of the upper part of the San Pedro Formation.[4]
- Zone VI corresponds to the Silverado aquifer and within the Charnock Sub-Basin is divided into three sub-zones (VIa, VIb, and VIc).
- Zone VII is a transition zone between the Silverado aquifer and low-permeability sediments in the lower San Pedro and upper Pico formations.

In addition, more recent aquifer test results (as reported in the Aquifer Report) were used along with lithologic and geophysical logs in refining the geometry of hydrostratigraphic zones included in the earlier conceptual hydrogeologic model (Geomatrix, 1999g) of the aquifer system. In general, the variations in hydraulic conductivity indicated by EBF test data from the production wells
corresponded with hydrostratigraphic zones of the Silverado aquifer identified in the prior Geomatrix Report. Based on the EBF test results, the hydrostratigraphic zone previously identified as the lower portion of the Silverado aquifer (Zone VIc) was divided into an upper Zone (6u) and a lower zone (6l). The EBF results indicate that approximately 68 to 78 percent of the water pumped from wells at the COSM Charnock well field is produced from hydrostratigraphic Zone 6u.

Aquifer Properties

- Estimated values of transmissivity for the Charnock Sub-Basin include previously reported values, calculated values from time-drawdown data, and calculated values from measurements of specific capacity. Estimated transmissivities for the Silverado aquifer range from 10,000 to nearly 200,000 gallons per day per foot (gpd/ft) (or about 1,300 to 26,700 ft^2/day).

- Values and estimates of hydraulic conductivity for the Charnock Sub-Basin include previously reported values, estimates from information about aquifer transmissivity and thickness, estimates from grain-size distribution data, and results from laboratory testing. Estimates of horizontal hydraulic conductivity range from 20 to 250 ft/day for aquifer zones to 1 ft/day or less for aquitard zones. Laboratory results for vertical hydraulic conductivity range from approximately 1×10^{-4} to 7×10^{-2} ft/day for silts and clays, 5×10^{-4}

[4] The sediments of Zone IV in the area of Sepulveda and Venice Boulevards is also referred to as the Shallow Unconfined Aquifer ("Unnamed Aquifer" in SOW) in various hydrogeologic reports for the Sub-Basin.

to 0.7 ft/day for silty and clayey sands, $1x10^{-2}$ ft/day for sands with some silt and clay, and 0.1 to 30 ft/day for clean sands.

- Reported estimates of storage coefficients and analyses of the SCWC water level drawdown data suggest that storativities range from $4x10^{-5}$ to $2x10^{-2}$ and that specific yields range from 0.01 to 0.3 for the Silverado Aquifer in the Charnock Sub-Basin.

- Available porosity values generally range from 30 to 50 percent, averaging about 47 percent for silts and clays, 43 percent for clayey and silty sands, and 38 percent for clean sands and gravels.

In July 1999 Geomatrix presented the results of a full-scale 850 gpm, 72-hour pump test on well Charnock-16 (CH-16) located in the COSM Charnock well field. Results of the analyses of that aquifer test indicate that the aquifer system exhibits a leaky (semi-confined) behavior. Analysis of data from wells screened in the Silverado aquifer provided transmissivity values averaging approximately 74,800 to 157,000 gpd/ft (about 10,000 to 21,000 ft^2/d). Analytical methods based on conceptual models that considered the entire aquifer system (Silverado aquifer plus overlying saturated sediments) yielded transmissivity values generally averaging between about 82,300 to 134,600 gpd/ft (11,000 and 18,000 ft^2/d). Storage coefficients obtained from the analytical solutions were generally on the order of 10^{-4} to 10^{-2}. Bulk horizontal hydraulic conductivity calculated using transmissivity values and assumed aquifer thickness of 200 to 300 feet ranged from about 40 to 80 ft/d.

Analytical solutions for leaky aquifers with aquitard storage provided relatively low leakage coefficient values, indicating relatively low vertical hydraulic conductivity of the aquitard zones (about 0.16 to 2 ft/d, assuming an aquitard thickness of 30 feet and equal storage coefficients for the aquitard and aquifer). An assumed lesser aquitard thickness would result in proportionally lower calculated values for vertical hydraulic conductivity of the aquitard zone. Aquitard vertical hydraulic conductivity calculated using the Neuman-Witherspoon ratio method ranged between about 0.0005 and 1.5 ft/d, based on an assumed aquitard thickness of 20 ft and assumed aquitard storativity of 10^{-4} to 10^{-2}.

Subsequent the aquifer test, Geomatrix refined the aquifer properties by sensitivity studies on an existing numerical flow model.

Groundwater Occurrence and Movement

The Silverado aquifer and the saturated zones above and below it comprise a heterogeneous, water-producing zone that contains individual zones of relatively high permeability and zones comprising heterogeneous, locally discontinuous aquitards (the Silverado itself is relatively very homogeneous in the x,y directions as would be expected in the predominantly shallow marine depositional environment). Estimates of the storage coefficient and the generally stratified nature of the aquifer system suggest predominantly confined to semi-confined behavior. Site-specific data indicate local discontinuous perched groundwater conditions.[5]

Historical water level data are relatively abundant for the 1930s through the mid-1960s. Within the Charnock Sub-Basin, water levels reflect the influence of historical groundwater extractions from the Sub-Basin's well fields. From 1930 to 1960, groundwater levels experienced two major cycles of drawdown and recovery in response to well field operations. Groundwater levels reached historic lows (e.g., -110 feet msl) in 1940-41 coinciding with historical maximum groundwater production. Water levels were at -5 to -60 feet msl during periods of water level recovery such as 1945.

Groundwater levels in the Coastal and Crestal Sub-Basins are generally 10 to 40 ft higher than in nearby areas of the Charnock Sub-Basin, supportive of the inferred partial hydraulic barrier attributed to the Charnock and Overland Avenue Faults. The influence of well field pumping on water levels immediately across the Charnock Fault is uncertain, however.

Under moderate agricultural pumping early this century, groundwater apparently occurred above the offset of the Charnock and Overland Avenue Faults (in deposits overlying and unaffected by the faults) and flowed southwesterly toward areas of discharge along the Ballona Creek and near the Pacific Ocean. With increased pumping, groundwater elevations dropped into the faulted (offset) deposits. This may have resulted in southeasterly flow through the Charnock Sub-Basin toward the Ballona Creek. With continued heavy pumping from the municipal well fields, the gradient within the southeastern half of the Sub-Basin reversed northwestward toward the well fields. In recent years prior to 1996, the direction of groundwater flow within the Charnock Sub-Basin generally has paralleled the bounding Charnock and Overland Avenue Faults, then moved radially inward toward the Sub-Basin well fields. Groundwater levels in the Coastal Sub-Basin indicate a relatively flat gradient, whereas groundwater levels in the Crestal Sub-Basin indicate south-southeasterly flow generally parallel to the Overland Avenue Fault.

Groundwater pumping ceased at the COSM Charnock well field in June 1996 and at the SCWC Charnock well field in October 1996, allowing regional groundwater levels to recover. As of June 1997, groundwater levels within the Silverado aquifer had recovered more than 25 feet at

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5 Perched groundwater will not be addressed explicitly in the groundwater flow model, which focuses on groundwater flow in the continuously saturated aquifer zones of the Charnock Sub-Basin.

the COSM Charnock well field and approximately 20 feet as far south as Sepulveda and Venice Boulevards. During this period of groundwater recovery the groundwater gradient has been to the southeast.

Under pumping conditions, a downward vertical gradient potential exists between wells screened above the Silverado aquifer and those screened within the upper part of the Silverado aquifer. At sites near Sepulveda and Venice Boulevards approximately 0.5 miles southeast of the well fields, May and June 1996 groundwater levels within shallow wells were approximately 15 to 20 feet higher than levels in the deeper wells (Wayne Perry, 1997, Woodward Clyde, 1997). By 1997, approximately one year after pumping ceased at the COSM Charnock well field, groundwater levels in the two zones had become similar.

Groundwater Balance

In the Geomatrix Report (1997g), estimates of the balance of groundwater inflows, outflows, and changes in storage for the Charnock Sub-Basin for selected periods and average conditions were presented. Except for recorded amounts of groundwater extraction and injection, the components of the groundwater balance must be estimated. To reflect uncertainties associated with these estimates, many are presented as ranges.

The groundwater inflow components include areal recharge from precipitation and water use, groundwater inflow across the Sub-Basin boundaries, and potential point and/or line sources of recharge.

- Areal recharge to the Charnock Sub-Basin occurs through the deep percolation of excess precipitation and delivered water. A portion of delivered water becomes groundwater recharge by leakage from water distribution lines, deep percolation of water applied for irrigation in excess of evapotranspiration, and exfiltration from sewers. Geomatrix (1997g) estimated that areal recharge in the Charnock Sub-Basin is approximately 7 to 14 in/yr based on the following assumptions:

    - The rate of areal recharge is similar to rates estimated previously by others for other urbanized basins in southern California.

    - Estimated average recharge from precipitation in the Charnock Sub-Basin is 1.5 to 2.0 in/yr under current urban conditions.
    - Ten to twenty percent of delivered water becomes recharge. This assumption, combined with Geomatrix's estimate that an average of 4.9 ac-ft/ac/yr is delivered in

the Charnock Sub-Basin, suggests that the average areal rate of delivered water recharge is approximately 6 to 12 in/yr.

- Other observations relating to areal recharge include the following.

  - Rates of areal recharge from precipitation and delivered water may have changed through time as a function of development in the Charnock Sub-Basin.

  - Although the precipitation record contains significant variability, rainfall amounts appear to have little or no correlation with regional groundwater level hydrographs of the Silverado water levels or historical rates of groundwater pumping. The vadose zone and perching layers attenuate downward movement of water from precipitation and water delivery and smooth the rate of areal recharge. The perched zone hydrographs in the Sepulveda & Venice and Sepulveda & Palm area do however show a strong calibration to precipitation events.

  - Local variations in areal recharge are assumed to be relatively minor.

- The Geomatrix Report (1997g) presented estimates of subsurface groundwater inflow to the Charnock Sub-Basin as follows.

  - Northwest Boundary: Relatively high rates of rainfall and runoff in the Santa Monica Mountains provide a significant source of recharge to the Charnock Sub-Basin. Based on a watershed water balance, average recharge from this boundary is approximately 2900 ac-ft/yr, with a potential range between 870 and 4900 ac-ft/yr. Using a Darcy's law approach, groundwater inflow from this boundary ranges from approximately 900 to 6600 ac-ft/yr, with an intermediate estimate of about 3800 ac-ft/yr.

  - Southeast Boundary: Under pumping conditions, groundwater flows into the Charnock Sub-Basin across its southeast boundary. Prior estimates of this inflow have equaled 25 to 40 percent of the inflow from the Santa Monica Mountains. Geomatrix (1997g) estimated 700 to 2000 ac-ft/yr, with a mid-range estimate of approximately 1400 ac-ft/yr, using Darcy's law. Under current non-pumping conditions, this could become an outflow boundary.

- Southwest and Northeast Fault Boundaries: Groundwater level differences across the Charnock and Overland Avenue Faults indicate that these faults form partial barriers to groundwater flow. Geomatrix (1997g) used a water balance approach to estimate that the potential amount of groundwater flow into the Sub-Basin across these faults may range from 0 to 500 ac-ft/yr.

- Basal Boundary: Groundwater inflow from sediments below the Silverado aquifer across this boundary is assumed to be negligible because of the low-permeability sediments at the base of the Silverado aquifer.

• Potential point/line sources of groundwater recharge in the Charnock Sub-Basin include injection wells and leakage from lined and unlined stream channels and regional water supply distribution lines.

- Selected wells in the COSM Charnock well field were used for groundwater injection during 1975 to 1988 at an average rate of 1200 ac-ft/yr.

- Lined channels in the Charnock Sub-Basin probably do not represent sources of recharge under current conditions, but may have acted as line sources of recharge prior to about 1960 when then channels were unlined.

The groundwater outflow components of the Charnock Sub-Basin include well extractions, potential boundary outflows, and potential discharge to streams.

• Groundwater pumping: Groundwater development in the West Coast basin began about 1870. Within the Charnock Sub-Basin, the COSM Charnock well field began operation in 1924, followed by the SCWC Sepulveda well field in 1926 and the SCWC Charnock well field in 1928. Groundwater extraction at the SCWC Sepulveda well field effectively ceased in 1960. The two Charnock well fields operated more or less continuously until June (COSM) and October (SCWC) 1996. SCWC also operated well fields in the Crestal and Coastal Sub-Basins from 1914 to the early 1950s.

During 1931 to 1996, net groundwater extractions from the Charnock Sub-Basin averaged about 6200 ac-ft/yr, and ranged from 1400 ac-ft/yr in 1979 to nearly 14,500 ac-ft/yr in 1940. Agricultural groundwater use was about 2000 ac-ft/yr from 1931 to 1945, but declined rapidly as agricultural land was converted to suburban and industrial use during the postwar period.

- Boundaries: Under pumping conditions, the native groundwater gradient is reversed in the southeast part of the Charnock Sub-Basin such that little or no groundwater outflow or discharge occurs.

Changes in groundwater storage within the Charnock Sub-Basin are indicated by overall rises and declines in groundwater levels. Because these water level fluctuations generally are assumed to occur under water table conditions, changes in groundwater storage may be estimated as the change in volume of saturated aquifer multiplied by a representative value of specific yield during 1945 through 1950, a period of falling groundwater levels. For example, using a reasonable range of estimated values for specific yield (0.05 to 0.25) results in a calculated decrease in groundwater storage that ranges from 650 to 3300 ac-ft/yr during 1945 through 1950, a period of falling groundwater levels.

Based on the long-term sustainability of well field yields and absence of downward-trending groundwater levels, it is reasonable to assume a zero net change in groundwater storage, i.e., that average groundwater inflows and outflows are equal. The following is an example of an estimate of recharge and inflow that sums to the average rate of groundwater extraction:

	ac-ft/yr
Areal recharge	2500
Santa Monica Mountain boundary inflow	2500
Ballona escarpment boundary inflow	700
Charnock and Overland Ave. Faults boundary inflow	500
Total	6200

Alternative distributions of the net inflows of water to the Sub-Basin, however, would also be consistent with the historical average rate of groundwater extraction.[6]

[6] Although groundwater pumping in this range has been considered to be the "safe yield" for the Sub-Basin, the development of this estimate only considered the available water volume in the basin, not the quality of the water resource. The deeper, more predictive groundwater zones of the Sub-Basin may be relatively vulnerable to various sources of shallower contamination, however, particularly when the available water resource is pumped at rates at or above its sustainable capacity. The management of the groundwater resources in the Sub-Basin for potable water supplies should consider both water supply and water quality protection in determining a safe level of long-term groundwater extraction.

Approach for Numerical Modeling of Groundwater Flow

The purpose of the numerical model in this project is to assess groundwater flow and water quality management and restoration within the Charnock Sub-Basin under a variety of groundwater extraction scenarios. Based on the calculated flow fields, ENVIRON will use particle tracking to assess flow lines capture zones and zones of groundwater containment associated with groundwater extraction alternatives.

ENVIRON will use as a basis and starting point (changing/refining as necessary) the model already developed by Geomatrix, the Respondents, Chevron and Exxon. That model was developed with MODFLOW (McDonald and Harbaugh, 1988), a widely used and accepted computer code developed by the USGS for modeling groundwater flow. MODFLOW is capable of simulating the physical processes that influence groundwater flow within the Charnock Sub-Basin (i.e., three-dimensional flow through anisotropic, heterogeneous porous media bounded by irregular surfaces). ENVIRON will use the MODFLOW results and a separate computer code for particle tracking MODPATH (Pollock, 1989, 1994) to estimate a variety of source removal and capture zone scenarios. MODPATH is well documented and verified against analytical solutions for specific flow scenarios, and has been widely accepted by regulatory agencies.

The model domain centers on the COSM and SCWC Charnock well fields. It includes the Charnock Sub-Basin from the Ballona escarpment in the southeast to Olympic Avenue in the northwest. To allow explicit simulation of particle tracking across the faults, Geomatrix (1997g) has previously placed the southwestern and northeastern model boundaries approximately 6000 feet outboard, (east and west) from the Charnock and Overland Avenue Faults. Thus, the model domain includes parts of the adjoining Coastal and Crestal Sub-Basins.

Axes of the finite-difference grid are aligned with the northwest-southeast trend of the sub-basin to optimize model size and accurately represent model boundaries and faults. The boundaries of the model domain will be treated as either no flow, specified flow, or head-dependent flow. A specified flow boundary at the top of the uppermost active model layer will represent recharge at a rate of approximately 7 to 14 in/yr. The base of the water-producing zone will be represented as a no-flow boundary at the base of the deepest model layer.

The grid developed for the numerical model is aligned with the general trend of the Charnock Sub-Basin, such that grid columns coincide with the trend of the Charnock and Overland Avenue Faults. The grid has relatively small cell sizes (20 feet by 20 feet) in areas where significant changes in hydraulic gradient are expected to occur (e.g., near the well fields). Cell sizes expand toward the model boundaries, maintaining an aspect ratio of no more than 5:1 in the vicinity of the Charnock well fields and 10:1 elsewhere. The model grid may be expanded laterally in the future to facilitate the evaluation of remedial alternatives involving relocation of groundwater pumping centers. In addition, the model grid size will likely be refined in areas to accurately simulate sub-regional pumping/remediation.

The model layer discretization closely reflects the conceptual hydrostratigraphic layering scheme. Elevations of hydrostratigraphic zone surfaces are represented by incorporating them as surfaces within the numerical model and subdividing hydrostratigraphic zones as necessary.

Aquifer properties to be assigned to the model include hydraulic conductivity, storage coefficient, and porosity. The initial zonation of aquifer parameters will be consistent with the hydrostratigraphic discontinuities between sub-basins. As mentioned at the beginning of this subsection, Geomatrix developed a MODFLOW model for the Charnock Sub-Basin. Additionally, with single and multiparameter sensitivity analyses, Geomatrix refined the aquifer properties. ENVIRON will base the initial values of aquifer properties for the numerical model on its compilation and analysis of available data and use as a basis the latest version of the Geomatrix model. The hydraulic conductivity of individual model cells will be horizontally isotropic. Reasonable values of vertical hydraulic conductivities will be achieved by assuming ratios of vertical to horizontal anisotropy. During model calibration, these parameters may have to be adjusted within reasonable ranges to improve calibration of the numerical model.

While the Silverado Aquifer itself is relatively homogenous, heterogeneities exist within the identified hydrostratigraphic zones (e.g., discontinuous aquitards). Initially, uniform values representative of equivalent vertical and horizontal hydraulic conductivities will be assigned. Where supported by data and deemed necessary for calibration, ENVIRON will utilize a deterministic zonation of hydraulic conductivity based on observed lithologic variability and interpreted depositional patterns within each model layer. However, the study area is characterized by local areas of relatively abundant and variable lithologic data separated by areas for which data are sparse. For this reason, ENVIRON will consider applying a stochastic approach to represent observed degrees of spatial variability within selected depth zones.

Steep hydraulic gradients across the Charnock and Overland Avenue Faults suggest a relatively low transmissivity along both faults at depth. ENVIRON initially will attempt to model groundwater conditions in the vicinity of the faults by representing the interpreted offset of hydrostratgraphic zones across each fault. If calibration results necessitate, ENVIRON will implement a zone of cells having lower hydraulic conductivity within the vicinity of each fault.

Historical groundwater extraction represents the principal model stress against which the numerical model will be calibrated. At each well location, extraction rates will be distributed among model layers based on well screen information and layer transmissivities. Where possible, known extraction rates will be specified at each well. When data availability and reliability do not permit, known or estimated extraction rates will be distributed between appropriate wells.

During model calibration, ENVIRON will adjust certain parameters, potentially including aquifer properties, boundary conditions, and water balance components, to yield a set of parameters that simulate groundwater levels and fluxes within a reasonable range of error from observed values. ENVIRON will calibrate the model in two steps: first, to quasi-steady-state hydrologic conditions; and second, to transient hydrologic conditions. The two-step approach allows a preliminary estimation of hydraulic conductivities, boundary conditions, and water balance during the steady-state calibration, followed by refinement of those parameter values and calibration of storage parameters during the transient calibration. The transient calibration will achieve a reasonably good match between observed and simulated groundwater levels and fluxes under a range of stress conditions representative of potential conditions. An additional calibration period will encompass the water level recovery that has occurred since pumping at the COSM and SCWC Charnock well fields ceased in mid- to late 1996. ENVIRON will perform a sensitivity analysis to estimate the uncertainty in the calibrated model caused by uncertainty in the estimates of model parameters.

ENVIRON will use particle tracking to visualize the results of groundwater modeling. Using the simulated groundwater flow fields, forward tracking will trace groundwater flow downgradient from selected starting points, and backward tracking will trace the origin of groundwater flow upgradient from selected end points (e.g., a pumping well). ENVIRON will develop baseline and alternative assumptions for future groundwater pumping and recharge within the area affecting the model. ENVIRON will evaluate current conditions and various extraction alternatives. This evaluation may include:

- forward particle tracking to assess the movement of groundwater under current conditions (no groundwater extraction)
- backward particle tracking to delineate the simulated zones of groundwater containment provided by existing or potential new extraction wells
- forward particle tracking to assess the movement of groundwater for various groundwater extraction scenarios.